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LOW EFFICIENCY CONTROL MEASURES FOR JET ENGINE TEST CELLS

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This report summarizes the findings of low cost, relatively low efficiency emission control measures for reduction of jet engine test cell opacity to less than 20%. The recommended cost effective opacity reduction system consists of an effective water spray system; a glass fiber mist eliminator; a medium efficiency, high velocity, throw-away type glass fiber filter media; and a reduced test cell discharge area. The report discusses the following topics: control methods, opacity, scrubbers, demisters, and filters. 410 988

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PREFACE

This study was accomplished to determine if it is feasible to reduce the opacity of turbine engine test cell smoke emission plumes to below 20 percent through the use of relatively low efficiency control procedures directed specifically at the opacity problem. It was envisioned that by use of these procedures, opacity goals might be met at a cost much below that of conventional particulate control systems. The work was performed by Dr Dale A. Lundgren, 1411 NW 50th Terrace, Gainesville FL 32605, under contract to Detachment 1, Armament Development and Test Center (Civil and Environmental Engineering Development Office), Tyndall AFB FL 32403, where Major Peter S. Daley was the project officer.

This report has been reviewed by the Office of Information (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

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SECTION I
SUMMARY

The object of this study was to find and recommend a cost effective (inexpensive) method for jet engine test cell opacity control which is compatible with an existing test cell in all normal modes of operation. Testing of a J-57 engine in a turbine engine test cell located at McClellan Air Force Base, Sacramento, California, was used as a model situation on which to base this study. Control of any similar engine in any similar test cell would be comparable because the jet engine test cell particle size distribution data obtained by Grems (1), and used for all calculations, are believed to present the most difficult to control situation for opacity reduction.

Both standard and novel approaches to particle removal were considered. Applications of standard control methods to a turbine engine test cell have been discussed in some detail in cited references (2, 3) and are not discussed in this report. Several specific topic areas are discussed to help the reader understand the recommendations of this study. This study was directed toward the control of an opacity problem. Therefore, a discussion of plume opacity is included which describes the special problem created by a large test cell discharge area. Plume opacity will be reduced by reducing this discharge area.

The high velocity gas stream leaving a turbine engine possesses a considerable amount of energy. A report by Springer (4) recommended redesign of the augmentor tube to behave as a Venturi scrubber in order to utilize this energy for particulate collection. This was a very reasonable recommendation and a similar recommendation was made in the project work statement for this study. The topic discussion on scrubbers explains why a Venturi scrubber cannot cause a significant reduction in plume opacity because of the submicron size aerosol found to exist in a jet engine exhaust plume. Liquid sprays, however, are recommended to completely cool the hot jet engine exhaust for reasons of safety, minimization of gas volume, and possible particle growth through condensation (which will aid in particle removal). Water spray rates are estimated at less than 1000 gpm for a 1,000,000 cfm gas flow rate (one gallon of water for each 1000 ft^3 of gas treated). This water usage rate is compatible with the present test cell system capabilities. (Venturi scrubbers normally require 3 to 10 gallons of water per 1000 ft^3 of gas treated.)

Because complete gas cooling by water sprays is recommended, some water mist must remain. A mist eliminator (demister) will be required to prevent the discharge of particle laden water droplets into the atmosphere and the problems associated with their fallout. A discussion of mist eliminators is concluded with a recommendation that a glass fiber mat mist eliminator be used because it is effective and is inexpensive.

The above mentioned water spray system, followed by an effective mist eliminator, will reduce the particulate mass emission rate but will not significantly reduce the plume opacity. A recommended discharge area reduction, by a factor of 4 or 5, will increase the gas discharge velocity to a desired

100 to 120 fps and will reduce the opacity because of the reduced plume diameter. An increase in discharge velocity does not affect mass emission rate but it does increase the effective stack height and atmospheric mixing which will result in a decrease in ground level pollutant concentration.

A final topic discussion, which forms the basis of a cost effective opacity control system, recommends the use of a glass fiber filter media to actively remove ∿50% of the opacity causing particles (those between ∿0.1 and 0.5 μm diameter). These particles only contribute about 20% of the total aerosol mass but they contribute about 80 to 90% of the aerosol opacity. Candidate filter media were selected and particle collection efficiency calculations performed over a range of particle size and filter face velocities. Several glass fiber filter media were selected which would operate at a face velocity compatible with that of a demister mat (∿10 fps) and remove about 50% of the opacity causing particles. The upstream side demisting filter and the downstream side particle collection filter would be packaged together in an easily removable holder of a convenient size, perhaps 3 ft by 3 ft by 6 inches deep. This would be a true aerosol control device and would reduce opacity to an acceptable level. This filter system approach would allow greater flexibility in obtaining various degrees of opacity control by selection of various filtration media. Final system design variables include degree of opacity reduction, system pressure drop, initial installation cost, filter replacement cost and filter replacement frequency (determined by filter loading characteristics). Recommended filter media would be a glass fiber throw-away type. This demister-filter bank could be positioned downstream of the augmentor tube outlet or attached to the present test cell outlet section.

A major limitation of the recommended filtration system could be rapid filter loading (pressure drop increase) which would require frequent filter replacement. Filter media can be selected which have good loading characteristics. Filter loading characteristics for a jet engine test cell aerosol should be experimentally verified to assure the optimum filter media selection.

If average cost data for an air pollution control system is used to estimate the capital cost of something as simple as a spray chamber, the indicated cost will be very high. For example, the recent articles by Neveril, Price and Engdahl (20) suggest a capital cost of $300,000 for a 1,000,000 acfm hot gas quencher. This cost would include a vessel, spray nozzles and supports constructed of carbon steel. Estimates of this type are of no value for retrofitting an existing facility, such as an existing jet engine test cell, where the housing (or vessel) is already in place.

Costs associated with design, construction, installation and operation of the proposed cost effective filtration system have not been fully determined. A first estimate of the approximate cost for construction and installation of a proposed opacity control system -- consisting of water spray nozzles, demister and a high velocity filter bank -- on a test cell like the one described by Grems (1) at McClellan Air Force Base would be $200,000. A minimum cost, temporary system, constructed from lumber and plywood could probably be built for \$100,000. A first estimate of design cost would be \$25,000. Filter bank replacement frequency is estimated as monthly, with filter replacement cost estimated at \$1,000 per filter change. These costs assume a nominal 600,000 acfm gas flow (cooled to about 100 to 120°F by water sprays) passing through a composite fiber mat demister -- glass fiber filter. Total filter area of 1000 ft^2 is based upon an average filter face velocity of 10 fps (600 fpm). Filter loading was calculated from mass emission data reported by Grems (1). Filter replacement cost was based upon filter cost data obtained from Mr. Roland Langlois, Owens-Corning Fiberglas Inc., Technical Center, Granville, Ohio.

SECTION II
INTRODUCTION

The Air Force routinely tests turbine engines in fixed test cells (jet engine test cells) which have been cited by air pollution regulatory agencies for visible emission violations, normally exceeding a 20% plume opacity limit. Efficient and effective, but expensive, techniques exist to control these visible emissions. Because of the very high gas flow rates to be treated (about one million cfm), these systems become extremely expensive (several million dollars) and are not considered cost effective because of the relatively low number of actual engine test hours which require efficient particle control and because of the relatively small quantity of particulate matter actually emitted from the test cell.

Compliance with opacity regulations normally requires a maximum of 50% control efficiency for a jet engine operating at its worst condition, a military power test. Therefore, relatively low effeciency (∿50% efficiency) and low cost techniques may effectively control test cell emissions, reduce their environmental effect and bring them in compliance with air pollution regulations. This study was directed towards identifying such methods.

SECTION III
BACKGROUND

Many studies have been conducted that relate directly to the jet engine test cell opacity problem. Items numbered 1 through 19 in the Reference Section (provided by the Air Force) comprise a rather complete list of past studies and indicate the extent of the Air Force effort to date. A complete review of these documents indicates that almost everything that relates to jet engine test cell emission control has been discussed. The joint Navy-Air Force study (2) and the Aerotherm report for the Environmental Protection Agency (3) provide excellent background and descriptive information on test cells, legislation, and conventional air pollution control techniques. Grems' report (1) provides very important data on the jet engine plume particle size distribution and opacity. Test results from the Jacksonville Naval Air Rework Facility jet engine test cell scrubber are also quite informative (5).

Few of the referenced reports have described a cost effective means to control plume opacity -- exclusive of fuel additives. A recent report by Springer (4) recommended redesign of the augmentor tube to approach the behavior of a Venturi scrubber as a cost effective alternate.

The current study started where the above reports left off. Information presented in references 1 through 19 was carefully reviewed and used to suggest other low cost alternates to opacity control. The final recommendations of this study are presented in the following section and the pertinent topic areas which support or explain these recommendations are discussed in the Topic Discussion Section.

SECTION IV
RECOMMENDATIONS

Based upon the results of this study, the following recommendations are made for a cost effective opacity reduction system:

1. Install an effective water cooling spray system capable of essentially complete cooling of the jet engine exhaust to the gas wet bulb temperature. (An excess water spray rate should be used to assure a slight water drainage from the mist eliminator.)

2. Install a glass fiber mesh mist eliminator to collect residual mist droplets greater than ∿10 μm diameter.

3. Install a medium efficiency, high velocity, throw-away type glass fiber filter media after the mist eliminator to remove about 50% of the opacity causing aerosol. This would probably be a composite filter media to assure optimum particle loading characteristics (maximum filter life).

4. Reduce the test cell discharge area so that at a military power test condition the actual discharge velocity is 120 fps, based upon a completely saturated stack gas condition.

A prototype control system should be designed or complete design specifications prepared in order to obtain an accurate installation cost estimate. Before a full test cell size unit is built, samples of demister-filter media should be tested to determine particle loading-pressure drop characteristics in order to assure proper filter media selection. A full scale system should then be built and tested at a facility such as McClellan Air Force Base.

SECTION V
TOPIC DISCUSSIONS

1. Control Methods

In this search for an inexpensive (cost effective) method to control jet engine test cell opacity, every described method of particulate removal was considered. Many of these methods were very inefficient on submicron size aerosols and were eliminated for that reason. Cyclone collectors, gravity settling chambers, various inertial devices and spray chambers are a few of the ineffective techniques. Various types of electrostatic devices were found to be efficient, but all are reasonably expensive. These include standard dry and wet plate electrostatic precipitators, and several novel devices such as those which use charged or neutral water droplets to collect charged particles. Standard baghouses (or fabric filter units) are very efficient but all were found to be expensive. Low velocity absolute type filters are also very efficient but very expensive when used on a one million cfm flow rate gas stream. Thermal precipitators were considered in some detail because of the hot jet exhaust stream. This approach, however, would have significantly interfered with the normal engine test cycle and caused several other problems. Nucleation and other particle growth techniques were carefully considered but none were inexpensive when applied to the high flow rate gas stream.

A simple particle collection technique capable of reducing plume opacity by about 50% was required. Considerations of the high gas flow rate, low mass emission rate and few hours of testing which actually violate the opacity standard have major impact on the economical use of standard air pollution control devices. These unacceptable approaches, because of cost or efficiency, are not discussed further in this report. The following topics, however, are considered pertinent to supporting the low cost, novel, filtration system which is recommended as a cost effective opacity control measure.

2. Opacity

Opacity is defined as the ratio of light attentuation to the incident light. Light transmittance is the ratio of light transmitted to the incident light. If an emissions plume is invisible, the transmittance is 100% and the opacity is zero. If a plume attenuates all incident light, it is totally opaque or has an opacity of 100% and a transmittance of zero.

Transmissometers (smoke meters) are instruments for monitoring transmittance. An in-stack transmissometer utilizes a light source to transmit a collimated light beam across a stack. The transmittance and opacity are functions of particle physical properties, concentration and optical path length. If the opacity of an exhaust stream is desired at the stack exit, but the measurement is made at some other location in the stack, the optical path length must be mathematically adjusted to the exit diameter (21). The following equation may be used to calculate transmission at the stack exit from the in-stack transmission if the respective path lengths are known.

$$\ell n\ (T_{ex}) = \frac{\ell_{ex}}{\ell_{in}}\ \ell n\ (T_{in}) \tag{1}$$

where: ℓ_n = natural log

T_{ex} = transmission at exit

T_{in} = transmission in-stack

ℓ_{ex} = stack diameter at exit

ℓ_{in} = transmissometer optical path length.

If in-stack transmissometer data is used to determine compliance with a plume opacity regulation, it is important to measure plume opacity over the visible range of the radiation spectrum. In-stack transmittance measurements do vary with wavelength of the light (21). *In situ* measurements of true plume opacity cannot be made when water droplets are present, such as after a scrubber, as the water droplets interfere. Water vapor does not interfere with opacity measurements.

Many other variables also affect plume opacity; some of these can be controlled, others cannot. The most important controllable variable, stack diameter, has been discussed. Another important variable is particle size. For any given particulate mass concentration, the smaller the particle size the more effective the light scattering and the greater the opacity. This general relationship is true down to a most effective lower size often assumed to be about 0.3 to 0.5 μm diameter. White smoke shows a maximum extinction per unit mass when the scattering particles are 0.6 μm diameter. Black smoke, however, shows a maximum extinction at about 0.15 μm diameter. Black and white particles effect optical transmittance to a very similar extent if the particles are greater than 1 μm diameter (22). The above holds for a very uniform size aerosol. For a very polydispersed aerosol (an aerosol covering a wide range of particle size), such as a jet engine exhaust, both an average or mean particle size and a measure of the size distribution spread must be known to predict an opacity effect. These variables plus stack gas temperature are considered controllable variables as opposed to the uncontrollable variables over which the test cell operator has little, if any, control.

Several of the uncontrollable factors affecting apparent plume opacity include: plume color vs. sky color, wind speed, atmospheric stability (turbulence), ambient air temperature and moisture content, distance of observer from stack, stack height (may be controllable), observer angle, sun angle, and human observer variability. A plume will appear most opaque at noon and will be more opaque in the far south than in the far north because of sun angle. A higher sun angle causes a higher apparent opacity. Other particle variables affecting plume opacity include particle density, shape and index of refraction.

Of the above variables, that of stack exit diameter is probably the most important because reducing it can result in a significant opacity decrease for little cost. In addition, a small stack is usually less expensive to construct than a large diameter stack. This stack diameter vs. opacity concept and other mentioned variables are discussed in an article by Weir (23).

The effect of stack discharge diameter on opacity (1-transmission) can be easily calculated using equation (1). Assume an initial opacity of 40%, transmission of 60%, from a stack diameter of 30 feet is to be reduced by decreasing the stack diameter to 15 feet. A new transmission of 77%, or opacity of 23%, is easily determined. Although this is a great simplification of the actual situation, the new stack exit opacity is correctly indicated by this simplification. Plume opacity after discharge into the atmosphere will normally be higher than at the stack exit plane. Based upon the observations and recommendations of others (personal communication with Dr. Michael Pilat, University of Washington, Seattle, Washington, August, 1978), the reduction in stack exit area will produce beneficial effects if the stack discharge velocity does not exceed $\sim$120 fps.

If the discharge area of a jet engine test cell is $\sim$690 ft^2 and the gas flow rate at maximum opacity is $\sim$1,000,000 cfm, the average discharge velocity would be $\sim$25 fps. Typical average velocities reported by Grems (1) at military power are $\sim$25 fps. A factor of 2 reduction in diameter (factor of 4 reduction in area) would raise the average velocity to $\sim$100 fps, still less than the maximum recommended velocity. Grems (1) stated that the exhaust area of a cell designed to test the largest jet engine in the Air Force inventory is only 85 feet^2.

Equation (1) can also be used to calculate the effect of plume dilution in the atmosphere with ambient air. If a constant average plume velocity were assumed (this is true only several diameters downstream from the stack exit), the result of a factor of 4 dilution (3 parts clean ambient air and 1 part stack gas) would be a factor of 2 increase in plume diameter. Transmission through this twice as large but one-fourth as concentrated plume would be increased and opacity decreased. If the plume or exhaust stream only slows down (no dilution), the net effect is the same as using a larger stack and the opacity increases. Most air pollution regulations state that a plume is to be evaluated (or read) at its point of maximum opacity. Therefore, it is the combination of slowing down and atmospheric dilution which determines the net effect or change in opacity after discharge. At discharge velocities above 120 fps the slowing down effect may become more important, suggesting an upper velocity limit beyond which no further opacity reduction can be obtained. At very low discharge velocities the opposite may result. At very low gas velocities there is insufficient energy in the gas stream to assist in a rapid turbulent mixing of the plume with ambient air. The dilution rate would then be determined by the atmospheric turbulence level.

If an elevated temperature, water saturated, black plume is discharged into a cooler atmosphere, the mixing with ambient air may cause a supersaturation of the gas stream and result in very rapid condensation of the excess water vapor onto existing particulate matter. This results in a masking of the black absorbing particles by larger, light scattering white water droplets.

Upon further dilution of this saturated water droplet laden gas stream with relatively dry ambient air, the water droplets evaporate leaving the highly diluted black absorbing particles. This expanded or larger diameter plume will have a decreased opacity, as shown by the previous calculation. There is no experimental data with which to quantitatively demonstrate this effect or otherwise enable a calculation to be made.

The overall effects of discharging a saturated plume into the atmosphere through a reduced diameter stack are as follows:

1) an initial reduction in opacity because of a decreased plume diameter, and,

2) a masking of the black plume by water droplets, followed by an opacity reduction resulting from additional dilution air entrained by the plume.

A combination of these two factors may allow a 40% opacity plume to meet a 20% opacity regulation. A greater reduction in opacity should not be expected because of the inexactness of these general relationships and other factors, mentioned earlier, that are involved in determining plume opacity.

For further information the reader should consult the report by Conner and Hodkinson (22) and the chapter by Nader (21). Articles by Weir, Jones, Papay, Calvert and Yung (24) and by Weir (23) should be read. Basic information on light scattering and particle optical measurement is contained in the works of Hodkinson (25), Kerker (26), McCartney (27), and van de Hulst (28).

3. Scrubbers

Removal of either vapor or particulate matter from a gas stream by means of a liquid is referred to as liquid scrubbing. This discussion will be limited to the removal of particulate matter. The basic mechanisms available for particle removal include inertial, electrostatic, gravitational, thermal and diffusional phenomena. The extent to which particulate matter is removed in a scrubber can be predicted from considerations of the basic collection mechanisms involved. For particles greater than 1 μm diameter, the inertial mechanism is normally dominant; for particles less than 0.1 μm diameter, the diffusional mechanism is normally dominant; for particles in the general 0.1 to 1.0 μm size range, neither diffusion or impaction is capable of efficient removal and other techniques must be used. Electrostatic techniques, involving charging the particles, the liquid droplets or both, can be used to obtain very efficient removal of the 0.1 to 1.0 μm particles. Condensation or particle growth techniques can increase the size of submicron particles so that inertial techniques can serve to remove them.

It is not the purpose of this write up to present a review of scrubber literature; only a few key references will be cited. A very complete study of wet scrubbers was funded by the Environmental Protection Agency (EPA). This report attempted to bring together all scrubber literature available up to that time (∿1970). An accompanying report presents a complete bibliography

(29, 30). As a follow-up to the above study, EPA sponsored a symposium on fine particle scrubbing in 1974 and the proceedings of this meeting were published by the EPA in the Journal of the Air Pollution Control Association (31). A few months ago a similar symposium was held and the proceedings will be published in the near future. EPA has, in the past eight years, funded several studies of new or novel techniques for fine particle control. These are available as NTIS reports from the U.S. Department of Commerce, Springfield, Virginia. As none of these new systems were considered cost effective for this project, none are referenced or discussed. Most air pollution text books and reference books contain chapters or sections on particle removal methods in general and wet scrubbing methods in particular. Two book chapters authored by Calvert are most appropriate to this discussion and the design approach suggested there will be used in this discussion (32, 33).

Particle removal by water sprays is a collection process which primarily involves the inertial impaction of gas borne particles onto liquid droplets, followed by the droplet removal (discussed in the next section on Demisters). Collection of a gas borne particle by a liquid droplet is directly related to the value of an inertial impaction parameter, K:

$$K = \frac{\rho_p \, D_p^{\,2} \, C \, U_g}{9 \, \mu_g \, D_d} \qquad (2)$$

where: ρ_p = particle density
D_p = particle diameter
C = Cunningham slip correction factor
U_g = gas velocity
μ_g = gas viscosity
D_d = drop diameter.

Calvert (33) uses the convenient technique of combining terms to allow use of an equivalent aerodynamic particle diameter, D_{pa}:

$$D_{pa} = D_p \sqrt{\rho_p \, C} \qquad (3)$$

This equivalent diameter substitution leads to:

$$K = \frac{D_{pa}^{\,2} \, U_g}{9 \, \mu_g \, D_d} \qquad (4)$$

Particle collection by a single liquid drop will increase, in a complex way, as the parameter value, K, increases and will reach a maximum of 1.0 (100%) when K >> 1. In a scrubber, the total particle collection efficiency is a function of the single droplet collection efficiency, η, which is a function of K, the total number of droplets, n, and the droplet size, D_d; all integrated over the droplet size distribution and particle size distribution. If the collection body is not a droplet but is a wetted surface, then the size and collection characteristics of that surface are used in the overall collection calculation. Discussion will be restricted to collection by droplets for the reason given below.

Generally, the most efficient and important class of particle scrubbers are those in which the liquid, normally water, is atomized by a high velocity gas stream. This category includes Venturi, orifice and other cocurrent flow spray scrubbers. Because of the inherent high gas velocity leaving a jet engine, this type of scrubber should be a natural consideration.

Contrary to what has been indicated in other reports (2, 3), a Venturi scrubber would have the desirable characteristic of obtaining higher efficiency at high flow rate conditions associated with maximum power engine tests where the highest efficiency is required. Maximum energy is also available when it is needed, or when the emitted pollutant levels are maximum. As suggested by Springer (4), the use of a Venturi scrubber approach was studied in detail. The result of this careful study indicates that a Venturi scrubber cannot solve the jet engine test cell opacity problem. The following shows how this conclusion was reached.

Calvert, and several other investigators (33), utilize the following type equation to describe particle collection in a gas-atomized spray system:

$$-\frac{dc}{c} = \frac{U_r}{U_g} \; \frac{3\, Q_\ell\, \eta}{2(U_g - U_r)\, A\, D_d}\, dZ \tag{5}$$

where:
- c = particle concentration
- U_g = gas velocity
- U_r = relative velocity (of gas vs. droplet)
- Q_ℓ = liquid volume flow
- η = single droplet efficiency
- A = cross sectional area
- D_d = droplet diameter
- Z = length of scrubbing section.

Most investigators use a digital computer to solve the above equation for a given particle size distribution, etc. Calvert's approach is much more reasonable for the problem at hand -- control of jet engine test cell opacity. It is unnecessary to go through several pages of calculations if one understands that the particles causing the opacity problems are the ones which must be removed.

The most useful data available on jet engine exhaust particle size distribution are that obtained by Grems (1). From this data and the basic nature of light scattering (refer to the section on Opacity), it is apparent that black plume opacity results almost entirely from the aerosol in the 0.1 to 0.5 μm equivalent aerodynamic diameter, D_{pa}, size range. Therefore, a significant opacity reduction requires a significant reduction of <0.5 μm size particulate matter. Calvert's solution of the above basic particle collection equation shows that 0.5 μm particles can only be removed under optimum conditions of high gas velocity, U_g, small droplet diameter, D_d, and relatively high liquid flow rates, Q_ℓ. It is also shown that <0.3 μm particles cannot be significantly removed even under optimum conditions. Using the particle distribution data of Grems (1) and simple but reasonable assumptions on maximum gas velocity, liquid flow rate, etc., a reasonable estimate of reduction in opacity would be 10%; this means a 40% opacity would be reduced to 36%.

If conservative calculations are made using realistic assumptions, based upon a composite of all data supplied on jet engine test cells, all results show that plume opacity cannot be controlled by conventional liquid scrubbing techniques (i.e., inertial, gravitational or diffusional deposition of gas borne particles on liquid droplets). Rather than repeat these calculations, the reader is referred to Section E, Gas Atomized Sprays, of the earlier referenced chapter by Calvert on "Scrubbing" (33).

Liquid sprays, however, can be used in an optimum way to assure complete cooling of the jet engine exhaust to the gas wet bulb temperature. This will reduce the gas volume to be treated by a subsequent particle control device; it will minimize any explosion or fire hazard; it will provide water vapor for condensation on the carbon particles; and water sprays will collect from 10 to 50% of the aerosol on a mass basis thereby lowering mass emissions, probably to well below the allowable mass emission limitations.

Results from extensive tests on a model crossflow packed scrubber pollution abatement system used to control opacity at the Jet Engine Test Cell in Jacksonville, Florida, indicate that the cooling water sprays may remove about 50% of the particulate mass (5). Tests were conducted with two types of packing material (Heile and Tellerettes) of various bed thicknesses with similar results being obtained for all tests. These tests indicate that the packed bed did not contribute to particle removal but did act as an effective demister. Because sprays are needed to reduce or control the jet exhaust temperature, the additional cost to use sprays optimally will be very minimal.

4. Demisters

Scrubbing systems normally require a mist eliminator, or demister, to remove gas borne liquid droplets before the scrubbed gas stream is discharged into the atmosphere. One good reference on the various types of mist eliminators and their general mode of operation was written by Straus (34).

Mist or droplet removal is basically the same as solid particle removal and similar or identical equipment is used. A mist, as used in this discussion, refers to a liquid aerosol in the general droplet size range from 10 to 1000 μm diameter. These large, spherical, liquid particles are easily removed by inertial, including centrifugal, techniques.

A major consideration in the selection and use of a mist eliminator is that of preventing reentrainment of the collected liquid. An opposite problem is the collection and subsequent evaporation of droplets from an unsaturated gas stream, which often leads to demister plugging. Complete evaporation of the droplets before their removal leaves only the non-volatile particulate matter and leads to demister plugging if collected, or increases the gas stream aerosol concentration if not collected.

The above are important considerations for a high temperature jet engine test cell and illustrate why complete cooling of a hot gas stream, down to the gas stream wet bulb temperature, is essential for many demister types, such as wire mesh pads or fibrous media. Draining of collected liquid from a fibrous or wire mesh greatly helps to flush away other collected solid particulate matter and retard plugging.

Relatively shallow beds (6" to 12" deep) of standard column packing materials are also often used as demisters. The Teller Environmental Systems, Inc. scrubber at the Naval Air Rework Facility in Jacksonville is an example (5).

Cyclones, multi-cyclones, and similar centrifugal devices are the simplest practical demisters. They tend to be self-cleaning, nonplugging, low pressure drop devices of high reliability. For use on high flow rate gas streams (100,000+ cfm), simple cyclones are very large in size and inefficient removers of less than 30 μm diameter droplets.

Mist eliminator design requires knowledge of the droplet size distribution to be removed. Knowing the method and conditions of liquid breakup, it is often possible to calculate the average droplet size. Using this droplet size, gas flow rate, gas temperature, liquid flow rate, and required droplet removal efficiency, it is possible to design or select a proper demister and determine its proper operating condition.

Various types of packed bed, plate and spray towers use wire mesh mist eliminators. A fine wire mesh demister is capable of efficient removal of droplets greater than $\sim$10 μm diameter at face velocities of $\sim$10 fps. At much higher velocities, removal efficiency is increased but liquid reentrainment becomes a problem.

Fiber mat mist eliminators are also widely used. A Brinks mist eliminator is a very popular example, although restricted to lower volume gas streams because of cost and pressure drop. Because of their low cost, glass fiber mats deserve careful study as mist eliminators. The principal mechanism for droplet removal in both wire and fiber mesh mist eliminators is inertial impaction, with the droplets impacting against the mat fibers. Several types of fibrous materials have been successfully used for fine droplet demisting. All mesh eliminators will require a simple support frame.

For the specific requirements of a jet engine test cell equipped with an efficient water spray system for gas cooling and/or particle collection, either a fibrous mat or wire mesh mist eliminator may be recommended because of its compact size and easy installation. A properly selected glass fiber mat would work as well as a wire mesh unit and be much less expensive. A stainless steel wire mesh unit would be easier to clean and would safely withstand the high temperature gas stream were the water spray system to fail. For use in a prototype system, a glass fiber mat would be much less expensive, easier to install and perform as well; therefore, a glass fiber mat is recommended.

5. Filters

Fibrous filters are the most widely used devices for removing particles from a gas stream, primarily because of their low cost and simplicity. Filters are capable of providing any desired degree of collection efficiency for either a submicron or supermicron size aerosol. Three basic characteristics of a filter are important:

1) Collection Efficiency- the extent to which a filter collects various size particles,

2) Pressure Drop- the energy required to draw a gas stream through the filter,

3) Filter Life- the particle loading-pressure drop relationship for the filter.

Filter efficiency and pressure drop can be calculated, thus it is possible to design a filter for a required efficiency or, conversely, calculate the efficiency and pressure drop of a given filter. Filter life cannot be calculated with reasonable accuracy and must be determined empirically, with filter life being a function of aerosol characteristics, filter design, gas velocity and filtration efficiency.

For high efficiency filters, most of the particulate matter is collected near the filter front surface and the filter life is determined primarily by total media area. For low efficiency filters, collection takes place through the filter depth and both filter roughness and surface area are important.

Modern fibrous filters are made with their fibers oriented more or less parallel to the plane of the filter, or transverse to the gas flow direction. All practical fiber filters are highly porous with fibers occupying typically <1% to 10% of the total filter mat volume. For these porous filters, one can assume a basic model in which the filter is made up of isolated cylindrical fibers, with axes perpendicular to the gas flow. Effects of neighboring fibers, actual fiber shape, etc. are then treated as corrections to the basic model. Efficiency of a total filter mat is calculated from the collection efficiency of the fibers comprising that mat.

Single fiber collection efficiency is defined as the ratio of the area cleared of particles by the fiber to the fiber projected area in the direction of flow. Under normal conditions the following mechanisms contribute to collection of particles in the size range of interest:

1) Brownian Diffusion - a small particle in air is bombarded by the gas molecules and exhibits a random motion due to the periodic nature of the collisions. If this random movement causes a particle to deviate from the streamline with which it was originally associated and to come into contact with the fiber, it is said to be collected by Brownian diffusion.

2) Interception - collection by interception results not from a force, but rather from a boundary condition. If a particle, in following an air streamline around a fiber, passes within one particle radius of the fiber, it is said to be collected by interception.

3) Inertial Impaction - when an air streamline is deflected by an obstacle such as a fiber, a particle, initially traveling along the streamline, will tend to move in a straight line due to its inertia. If crossing a streamline causes a particle to come into contact with a fiber, the collection is said to be attributed to inertial impaction.

4) Electrical Attraction - when a particle, a fiber, or both have electric charges, there is an electrical force affecting particle motion and collection. If an electrical force causes a particle to come into contact with a fiber, the collection is attributed to the electrical force.

In determining the contribution by any of the above mechanisms, it is assumed that any particle coming into contact with a fiber will stick to that fiber and will not be reentrained.

The contributions to single fiber efficiency by each mechanism, and the way in which these contributions add, are so complex that simplifying assumptions must be made in order to obtain solutions. Some of the theories add the individually determined contributions of the different mechanisms algebraically, while others combine them in the basic derivation.

By comparing experimental efficiency measurements on a range of filter types with the various theories, Whitby (35) found that the filtration theory developed by Torgeson (36) provided the best agreement of any single theory over the broadest range of conditions. Therefore, Torgeson's theory was used to calculate the collection efficiency of three commercial glass fiber filter media samples obtained from Owens-Corning Fiberglas Corp. Details of the basic calculation procedure are described in an article by Whitby and Lundgren (37).

The media selected for calculation were identical to media #1 and #2 and similar to media #3 used by Genoble in his research on high velocity filtration (38). Both experimental and theoretical results were presented for these three media as well as for a composite media of #1 and #3. Details of the above calculations and a copy of Genoble's thesis (38) were submitted earlier and will not be repeated as only the results are pertinent to this report. [For a complete compilation of filtration theories, the work of Pich (39) should be consulted. The book by Davies (40) and the paper by Kirsch and Stechkina (41) are also excellent references on filtration.]

Mathematical modeling is desirable for proper selection of a fibrous filter. Once the aerosol size distribution has been characterized and the collection requirements determined, a specific filter and operating condition can be selected. Available filter media differs significantly from an ideal model, but Genoble's data show that Torgeson's model adequately correlates theory with experimental efficiency measurements (38).

The effect a given filter will have on plume opacity can be estimated by averaging the particle collection efficiency over the 0.1 to 0.5 μm particle size range. Aerodynamic size distribution data obtained by Grems (1) will not allow making an exact calculation of aerosol opacity reduction. Reduction of opacity caused by particle removal in a narrow size range can be estimated, however.

Review of Grems data indicates that the 0.1 to 0.5 μm size range contributes only ~20% of the aerosol mass but most of the plume opacity. It is therefore necessary to remove about 50% of the 0.1 to 0.5 μm size aerosol mass to reduce opacity by 50%. Because this particle size range is the most difficult to remove, a significant (>50%) fraction of the larger aerosol will also be removed causing a somewhat greater than 50% reduction in opacity. The three filter media tested by Genoble (38) (for which collection efficiency calculations were made over a wide range of face velocities) would produce opacity reductions in the range from 20% to 90% (a 40% opacity would become 4% to 32%). This will allow the selection of a filter or composite of two filters to produce the desired opacity reduction. A composite of two filters is recommended because the filter life can be significantly extended, as shown by Genoble (38).

The most serious limitation of high velocity filtration is the aerosol mass loading considerations. Relatively low mass concentrations would be essential to prevent rapid pressure drop build up across the filter and frequent filter change. Filter loading characteristics could not be adequately estimated, therefore, a special filter configuration cannot be recommended at this time. Some experimental data must be obtained to determine filter loading characteristics for a jet engine exhaust aerosol.

Used filter media presents a solid waste disposal problem. At present, they can be disposed of in a normal sanitary landfill.

High velocity fiber filters will permit the required removal of opacity causing particles, despite their limitations. This control method appears to be a cost effective technique for jet engine test cell opacity control.

REFERENCES

1. Grems, III, B. C., "Plume Opacity and Particulate Emissions From a Jet Engine Test Cell," Master of Sciences Thesis, University of California, Davis (May, 1975).

2. Naval Air Systems Command, "Report of Joint Navy-Air Force Study of Air Emissions from Aircraft Engine Test Facilities," Washington, D.C. (January, 1977).

3. Blake, D. E., "Jet Engine Test Cells-Emissions and Control Measures," Aerotherm Final Report 76-189, on EPA contract 68-01-3158 (February, 1976).

4. Springer, C., "Effect of Cooling Water Spray on Turbine Engine Test Cell Emissions," 1976 USAS ASEE Sunmer Research Program AFOSR-TR-78-0348, Bolling Air Force Base, D.C., Vol. 1 (September, 1977).

5. Naval Air Rework Facility Report, "Jet Engine Test Cell Pollution Abatement Efficiency Tests," Naval Air Station, Jacksonville, Florida (1975).

6. Teller Environmental Systems, Inc., "Pollution Abatement Study and Systems Analysis for Jet Engine Test Cells," Gustan Getter Associates, New Rochelle, New York (February, 1970).

7. Geiger, J. R., "The Feasibility of Controlling Turbine Engine Test Cell Particulate Emissions With a Baghouse," CEEDO-TR-78-24, U.S. Air Force, Tyndall Air Force Base, Florida (February, 1978).

8. Klarman, A. F., "Gas Turbine Engine Particulate Measurement Technique," Report on Three Continuous Monitoring Systems, Naval Air Propulsion Test Center, Trenton, New Jersey (June, 1976).

9. Robson, F. L., A. S. Kesten, R. D. Lessard, "Analysis of Jet Engine Test Cell Pollution Abatement Methods," Tech. Report AFWL-TR-73-18, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico (May, 1973).

10. Teller Environmental Systems, Inc., "Report on Abatement of Particulate Emissions and Noise From Jet Engine Test Cells Including Reduction of Gas Flow with the TESI Augmentor-Scrubber System," N62467-70-C-0240, Naval Facilities Engineering Command, Charleston, South Carolina (1972).

11. Hoshizaki, H., A. D. Wood, S. Seidenstien, B. B. Brandalise and J. W. Meyer, "Development of an Analytical Correlation Between Gas Turbine Engine Smoke Production and Jet Plume Visibility," Report AFAPL-TR-76-29, Wright-Patterson Air Force Base, Ohio (January, 1976).

12. Martone, J. A., P. S. Daley, R. W. Boubel, "Sampling Submicrometer Particles Suspended in Near Sonic and Supersonic Free Jets," CEEDO-TR-77-48, Tyndall Air Force Base, Florida (October, 1977).

13. Broderick, A. J., M. J. Scotto and J. C. Sturm, "Particulates in Jet Aircraft Exhaust: Instrumentation and Initial Results," DOT Transportation Systems Center, Cambridge, Massachusetts, presented at 65th Annual Meeting AIChE (November, 1972).

14. Gearhart, J. W. and J. A. Benek, "Measurement of Pollutant Emissions From an Afterburning Turbojet Engine at Ground Level, Part I," AEDC-TR-72-64, Arnold Air Force Station, Tennessee (June, 1972).

15. Stockham, J. and H. Betz, "Study of Visible Exhaust Smoke From Aircraft Jet Engines," FAA-RD-71-22, Federal Aviation Administration, Washington, D.C. (June, 1971).

16. Champagne, D. L., "Standard Measurement of Aircraft Gas Turbine Engine Exhaust Smoke," ASME publication 71-GT-88, American Society of Mechanical Engineers, New York (1971).

17. Krimmel, J. A. and B. A. Longley-Cook, "The Effect of a Model Scrubber on Gaseous Emissions from a Gas Turbine Engine Test Cell," AESO-113-74-1, Naval Air Rework Facility, North Island, California (August, 1973).

18. Industrial Acoustics Company, "Aircooled System for Afterburning Jet Engine," IAC Bulletin 2.1203.0, Bronx, New York (1976).

19. IKOR, Inc., "Results of Testing of the IKOR Continuous Particulate Monitor in the Exhaust of a J-57 Gas Turbine Engine," IKOR, Inc., Burlington, Massachusetts (1974).

20. Neveril, R. B., J. U. Price and K. L. Engdahl, "Capital and Operating Costs of Selected Air Pollution Control Systems I & II," J. Air Poll. Control Assoc., 28:829 and 28:963 (1978).

21. Nader, J. S., in "Air Pollution," (A.C. Stern, ed.), Vol. III, 3rd Ed., Academic Press, Inc., New York, New York, pp. 589-645 (1976).

22. Conner, W. D. and J. R. Hodkinson, "Optical Properties and Visual Effects of Smoke-Stack Plumes," EPA AP-30, U.S. Environmental Protection Agency, Washington, D.C. (1967).

23. Weir, Jr., A., "Clearing the Opacity Issue," Env. Sci. and Tech., 11:561 (1977).

24. Weir, Jr., A., D. Jones, L. Papay, S. Calvert and S. Yung, "Factors Influencing Plume Opacity," Env. Sci. and Tech., 10:539 (1976).

25. Hodkinson, J. R., in "Aerosol Science," (C.N. Davies, ed.), Academic Press, New York, New York (1966).

26. Kerker, M., "The Scattering of Light and Other Electromagnet Radiation," Academic Press, New York, New York (1969).

27. McCartney, E. J., "Optics of the Atmosphere, Scattering by Molecules and Particles," John Wiley and Sons, New York (1976).

28. van de Hulst, H. C., "Light Scattering by Small Particles," John Wiley and Sons, New York (1957).

29. Calvert, S., J. Goldshmid, D. Leith and D. Mehta, "Scrubber Handbook," PB-213-016, NTIS, U.S. Department of Commerce, Springfield, Virginia (1972).

30. Calvert, S., J. Goldshmid, D. Leith and D. Mehta, "Final Report and References," PB-213-017, NTIS, U.S. Department of Commerce, Springfield, Virginia (1972).

31 Journal of the Air Pollution Control Association, 24:10 (1974).

32. Calvert, S., in "Air Pollution," (A.C. Stern, ed.), Vol. III, 2nd Ed., Chapter 46, p. 457, Academic Press, New York, New York (1968).

33. Calvert, S., in "Air Pollution," (A.C. Stern, ed.), Vol. IV, 3rd Ed., Chapter 6, p. 257, Academic Press, New York, New York (1977).

34. Straus, W., in "Air Pollution," (A.C. Stern, ed.), Vol. 14, 3rd Ed., Chapter 7, p. 293, Academic Press, New York, New York (1977).

35. Whitby, K. T., "Calculation of the Clean Fractional Efficiency of Low Media Density Filters," ASHRAE Journal (September, 1965).

36. Torgeson, W. L., "The Theoretical Collection Efficiency of Fibrous Filters Due to the Combined Effects of Inertia Diffusion and Interception," J-1057, Applied Sciences, Div. of Litton Ind., St. Paul, Minnesota (1962).

37. Whitby, K. T. and D. A. Lundgren, "Mechanics of Air Cleaning," Transactions of the ASAE, Vol. 8, No. 3 (1965).

38. Genoble, A. L., "High Velocity Filtration of Submicrometer Aerosols," Master of Engineering Thesis, University of Florida (June, 1978).

39. Pich, J., in "Filtration, Principles and Practices, Part I," (C. Orr, ed.), Marcel Dekker Inc., New York (1977).

40. Davies, C. N., "Air Filtration," Academic Press, New York, New York (1973).

41. Kirsh, A. A. and I. B. Stechkina, in "Aerosol Science," (D.T. Shaw, ed.), John Wiley and Sons, New York (1978).

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